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Review

Review of Long Wave Dynamics over Reefs and into Ports with Implication for Port Operations

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Abstract: This paper reviews the dynamics of infragravity (long-period) waves over reef systems and the consequences of these waves for operations in ports located behind reefs with particular attention to Western Australia. Swells which originate in the Southern Ocean generate long (infragravity) waves, which propagate to the coast. On the reef edge, the swell waves are largely dissipated, transferring energy to turbulence and heat but also in that process generating long wave energy. The remaining swell waves are dominated by the infragravity waves and propagate towards the mainland and into port basins where they cause moored ship motions with consequences for the operational downtime of the port's operations. When contemplating solutions to mitigate the impact of the long wave problems, these may be addressed from two sides: from the load side (waves) and the strength side (mooring). The former will be discussed in this paper.

Keywords: long waves; infragravity waves; ports; wave penetration; wave modeling; XBeach

1. Introduction

Long waves, sometimes also called "low frequency waves", "infragravity waves" or "subharmonic gravity waves", are waves that are forced in deeper water through subharmonic interactions of sea and swell wave components. Through short wave breaking on the reef edge these IG waves gain energy after which they propagate over the reef flat where they slowly decay due to bottom friction dissipation. This attenuation rate is slower than for the short waves, and thus infra-gravity waves dominate over swell waves near the coastline, and propagate into ports. Here, because of their long wave lengths, they can excite harbor seiching and ship motions, which have implications for the downtime of port operations. This operational downtime of moored vessels due to long wave activity has been a persistent problem at the Port of Geraldton, Western Australia, primarily due to surge motions (back and forth motion) of the vessels induced by offshore swell conditions.

This paper starts with a review of the field evidence of long waves and their dynamics. Then, we will focus on the Western Australian coast where field observations, modelling and the consequences for port operations with potential mitigation measures are discussed.

2. Field Evidence of Long Waves

Long waves were first observed by [1,2] in the field at La Jolla (CA, USA) and Perranporth (Cornwall, UK), respectively, which are both open coasts exposed to ocean swells. They both noticed a low-frequency signal at a time lag relative to incoming swell wave groups. They hypothesized that the lag was related to a reflection process near or on the coastline (Figure 1), but the observed time lags did not correspond well to the computed distance from the sensor to the coastline divided by the linear wave speed.

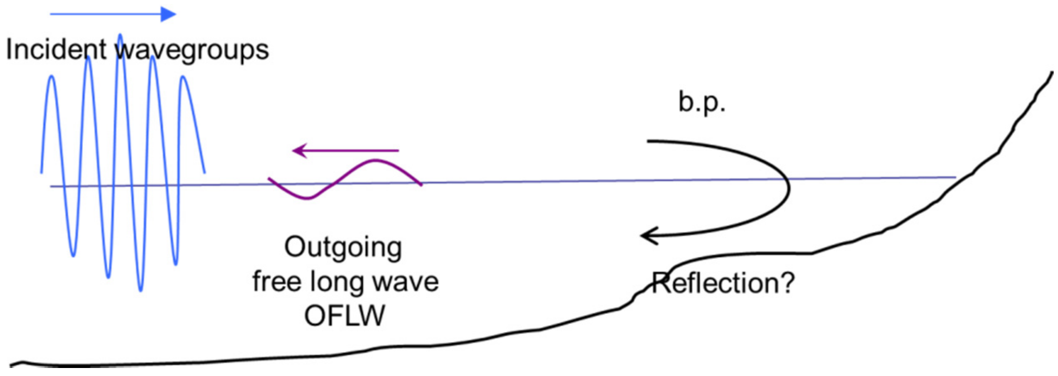

Figure 1. Theoretical sketch of incident wave groups on a coast and the outgoing free long wave (OFLW) reflecting off the breakpoint (b.p.).

These long wave motions were subsequently confirmed in a number of field campaigns (e.g., [3] and many studies thereafter) to contain a significant portion of the total energy in the wave field, especially in shallower water. They are found to be important in a number of nearshore processes such as dune erosion [4], nearshore bar formation, wave runup and overtopping.

In ports, incoming long waves can drive harbor seiches at the group frequency without breaking as was shown theoretically by [5,6] in laboratory experiments [5] and numerically [7]. These long waves, and especially the horizontal particle velocities can seriously interfere with harbor operations, cause costly delays and extreme motion and damage to ships, as was reported by [8].

3. Dynamics of Long Waves

From deep water to the coast, long waves undergo a number of processes including generation by nonlinear interaction, generation in the breaking process, and dissipation. In the remainder, we will discuss each aspect.

3.1. Generation of LW in Deep Water

Already in deeper water, LWs are generated: in the simplest conceptual description, consider two primary wave components in the sea/swell band (a so-called "bichromatic" wave field) propagating over a horizontal bottom. Since the two wave components travel at slightly different phase speeds the wave amplitudes of the components sometimes add up and sometimes cancel each other, forming a wave group pattern with sequences of higher and lower wave amplitudes.

Through nonlinear (second-order Stokes) interactions, the wave components force a longer-period wave at a frequency which is the difference of the frequencies of the two primary wave components. This wave is in anti-phase with the wave groups (its trough coincides with the crest of the wave group) and travels phase-locked, or bound, to the wave group, and is thus called the bound wave [9,10]. The latter authors provided a one-dimensional "equilibrium solution" that relates the bound wave amplitude to the radiation stress forcing provided by the short waves. The theoretical results were validated against observational data in the laboratory [11,12]. Physically, the formation of the bound wave can be understood as the waves with higher amplitudes pushing the mean water level down thus creating a trough. In compensation, a long wave crest occurs when the primary wave amplitudes are small.

In nature, the sea-swell wave field is composed of a large number of random components and through sub-harmonic interactions a spectrum of bound wave components is forced through mechanisms described by [13,14], which in effect is a 2-D generalization of [10]. These bound infragravity waves typically have frequencies in the range of 0.01–0.04 Hz, and in deeper water have amplitudes of mere centimeters.

3.2. Generation of LW during Short Wave Breaking

As the wave groups propagate towards the coast, the sea-swell waves start to shoal and ultimately break. In this process, energy is transferred from the sea-swell frequencies to the long waves, which ultimately may reach amplitudes near the shore of tens of centimeters and even meters. There are two mechanisms by which long waves are generated: by enhancement over the sloping seabed in the nearshore zone as a result of the continued forcing by the shoaling waves, up to the breakpoint [15,16], or even within the surf zone [17,18]. Alternatively, IG waves may be generated by a moving breakpoint [19], see Figure 2. The former is dominant on mild sloped topography while the latter is important on steeper slopes [20]. As will be shown below on steep fore reefs the breakpoint mechanism is dominant, and in this context the former mechanism is not considered further.

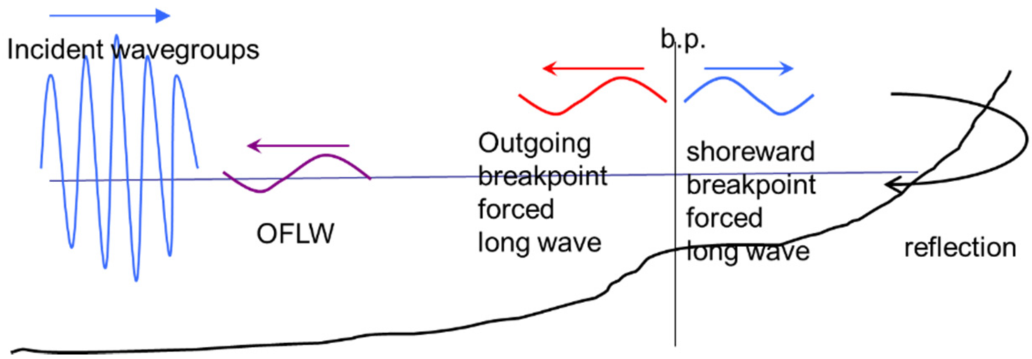

Figure 2. Theoretical sketch of [19]'s breakpoint mechanism which produces an outgoing breakpoint forced long wave radiating out directly to sea and a shoreward breakpoint forced long wave which propagates to the coast and then reflects.

3.3. Dissipation of LW

After IG waves are generated and are released from the wave groups, they propagate to the coast, where they may dissipate due to bottom friction [21,22], IG wave breaking [23], nonlinear transfer back to the short waves [24] or reflect off the coast and propagate back out to sea as free waves. Depending on their angle of incidence these waves may be refractively trapped on the coast as "edge waves" or may escape to deeper water as leaky waves. These leaky IG waves may propagate across ocean basins [25]. With this synopsis, we can understand Munk and Tuckers observations. The wave groups they observed forced long waves in their shoaling and breaking process. These waves travelled back from the beach to the observation site, which explains the measured time lag.

4. Long Waves on Reefs in WA

For the case of Western Australia, swell wave systems typically originate in the Southern Ocean with its frequent storms, but generation in Indian Ocean typhoon events is also possible. While the actual storms and typhoons may not reach or even be close to the Australian main land the associated swells (in the frequency range of 0.04–0.2 Hz) can propagate over large distances, see [26]. This can be seen in Figure 3, which shows the analysed wave height versus peak period for a station offshore of Geraldton. The lower cluster of data points are the primary short waves ("sea") which are forced by local winds and have frequencies above 0.1 Hz. They are limited in wave height, are expected to break substantially over the reef, and are no cause for ship mooring issues at Geraldton and are thus not considered further. The swell waves (in the frequency range between 0.004 and 0.1 Hz) have a broader range of wave heights and can potentially cause mooring problems by themselves. Moreover, as described in the literature cited above, these swell waves generate longer period waves, which for the case of Western Australia will be discussed further below.

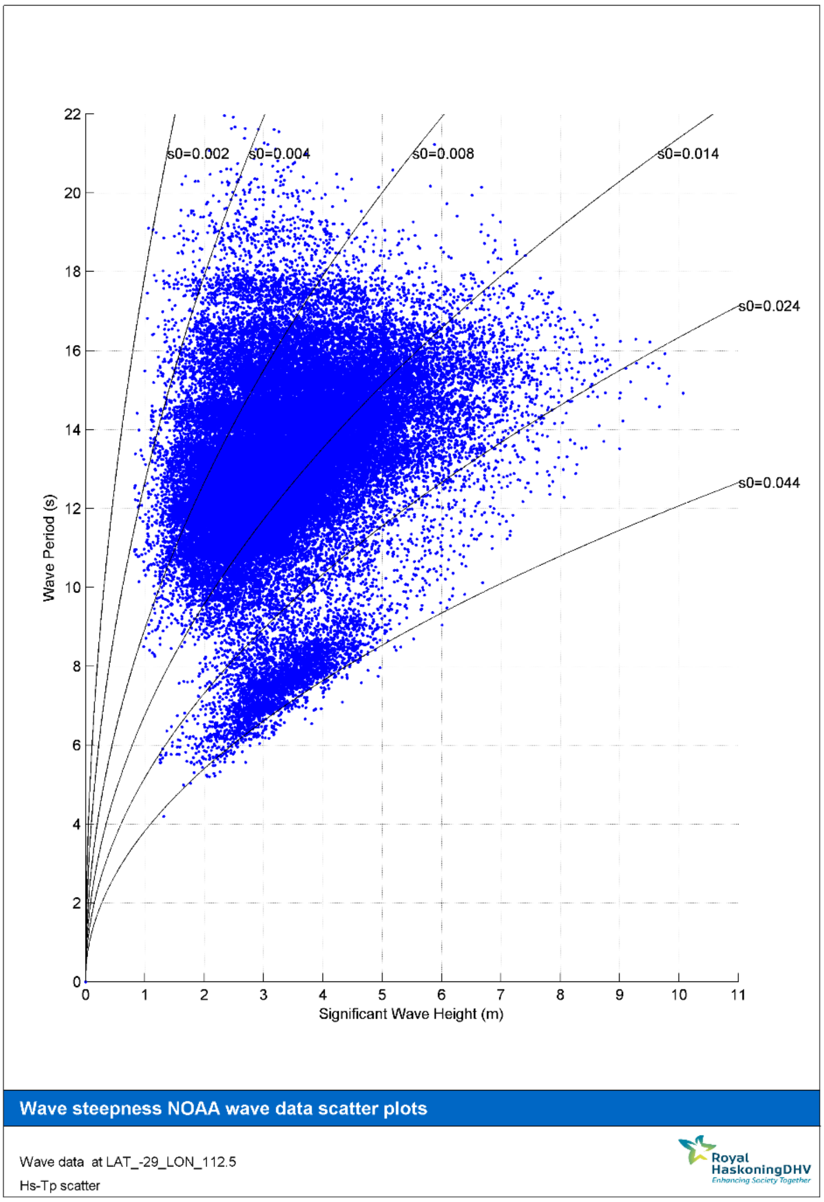

Figure 3. Wave height versus Peak period from NOAA data obtained offshore of Geraldton, WA showing a lower cluster of sea and a larger upper cluster of swell waves. Figure obtained with permission by Royal Haskoning/DHV.

As swell wave systems typically have lower frequencies and are more narrow-banded than sea waves [13], predicts a strong swell self-interaction and thus high variance of long waves. This process can be witnessed in Figure 4 which displays data obtained at Ningaloo Reef; some 700 km North of Geraldton, but exposed to similar swell systems. For a cross-shore transect (bottom right) we can observe the incident swell (frequencies larger than 0.04 Hz) at the offshore station C1 (top left). The arrival has clear swell characteristics of the longer period waves arriving first and thus displaying the diagonal streaks in the time/frequency plane. On the reef, the swell variance has largely dissipated, but the long wave variance increased. On the reef flat, both the swell wave and long wave height further decreases, most likely through bottom friction dissipation, but the long waves are more persistent and ultimately reach the shore.

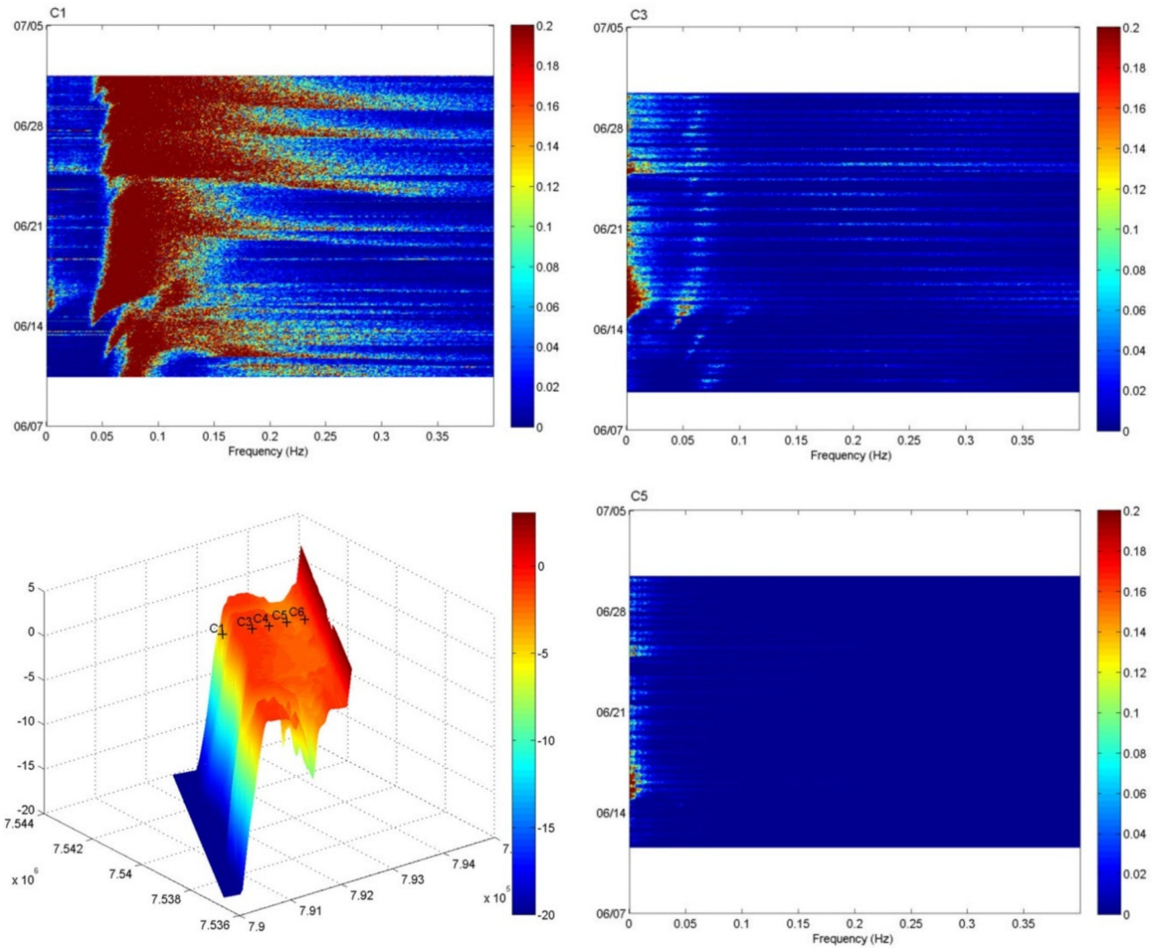

Figure 4. Measured swell and longwave variance at Ningaloo as a function of time in calendar days and frequency. (**Bottom right**) Transect with measurement stations. (**Top left**) Offshore station. Note the arrival of swell bands at 14/06 with $f = 0.05$ Hz. (**Top right and bottom right**) measured variance on reef. Note the disappearance of swell and the increase of long wave variance ($f < 0.04$ Hz). Data courtesy Ryan Lowe and Andrew Pomeroy, U. Western Australia.

These results show that the bulk of the water level variability was found to be contained within the IG frequency band. Thus, long wave motions are important in coral reef systems, which is confirmed by only a few other field extensive data sets [27–30]. The data set is limited due to a historical focus on the dynamics in the sea-swell band and means wave-driven flows on reef environments.

While Ningaloo is some distance to the North, the forcing, exposure and general bathymetry is similar to Geraldton. Hence, the most likely source location of IG wave generation is the reef slope and edge. From the reef edge, these IG waves propagate mostly on the shallows refracting along the channel edge (see Figure 5) towards the port entrance, where they enter the port. The IG wave periods are in the frequency range, and thus have wave lengths to which moored ships are sensitive. In particular, since these wave lengths are longer than a typical ship's length (but of the same order of magnitude), the ships react to the surface slope variation of the waves by "surging", *i.e.*, moving forward and backward along the quay. This motion causes large stresses on the lateral mooring systems (the ship's lines), with potential risk of line breakage and the cessation port loading operations. Hence, in the case of Geraldton, the swell waves themselves are not expected to be the direct cause of the ship mooring problems (except for berth 2) but rather indirectly through the IG waves which are generated by their interaction and the subsequent generation in the swell wave breaking process and further propagation of the IG waves into the port. In the port basin, some IG wave components may become resonant due to the ports dimensions (*i.e.*, the IG forcing amplifies eigenfrequencies in the port), which energizes certain frequency bands to which moored ship systems are sensitive. Even for non-resonant IG wave frequencies, certain moored ship systems may show large (resonant) responses and cause problems.

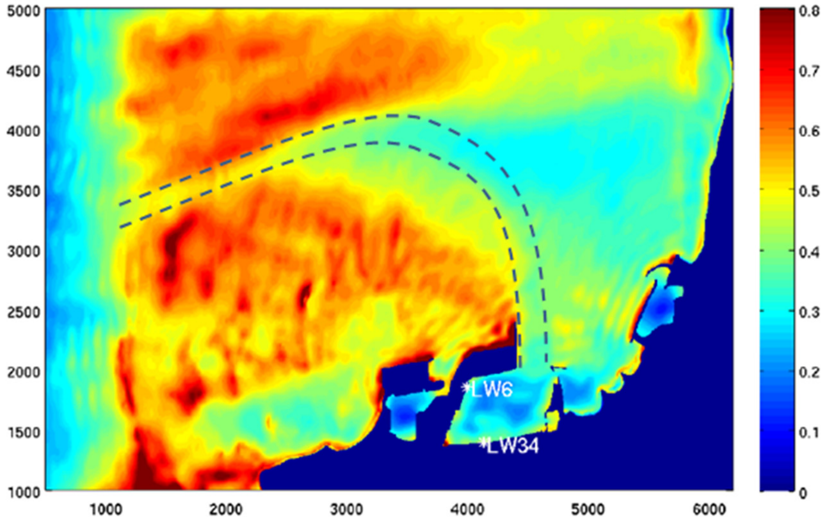

Figure 5. Example of FUNWAVE [31] long period wave significant wave height for an event on 2009-09-12. The boundary sea-swell Hs at Tp were 4.1 m and 17.3 s respectively. Units are in m. Figure courtesy Port of Gerardton, produced by MetOcean Solutions, with permission.

5. Numerical Modeling of Long Waves over Reefs

Despite the importance of IG wave motions to reefs and because of a lack of understanding hitherto of the nature of the problem, a diverse set of wave models have been applied to understand long wave transformation. Ray tracing models and wave action models such as SWAN [32] do not incorporate the necessary physics of transferring energy to lower harmonics, and are thus not suitable for this purpose.

Models that do capture the physics are in the wave resolving Boussinesq-class, or in the wave-group resolving class, such as XBeach [33]. The difference between the two models is that Boussinesq-type models resolve the wave shape, even of the short waves. However, this accuracy require a fine meshgrid which comes at a computational expense. In the literature, a few Boussinesq-type model applications to reefs are described: [34,35] each applied a 1D phase-resolving wave model to simulate both short wave and IG waves from smooth bed laboratory flume experiments. They found that the models were capable of predicting the overall wave transformation and spectral redistribution (including long waves) fairly well [36]. Described an application of a 2D Boussinesq-type model to fringing reefs. They showed good model comparison to laboratory data of solitary wave incident on a 1D and 2D reef in an application to a field site in Hawaii.

XBeach resolves the shape of the long waves and only the variation of the height of the short waves, which requires less resolution at a relative computational gain [37]. Applied the model in 2D mode to the above-mentioned data set of Ningaloo, and found good model-data agreement, see Figure 6.

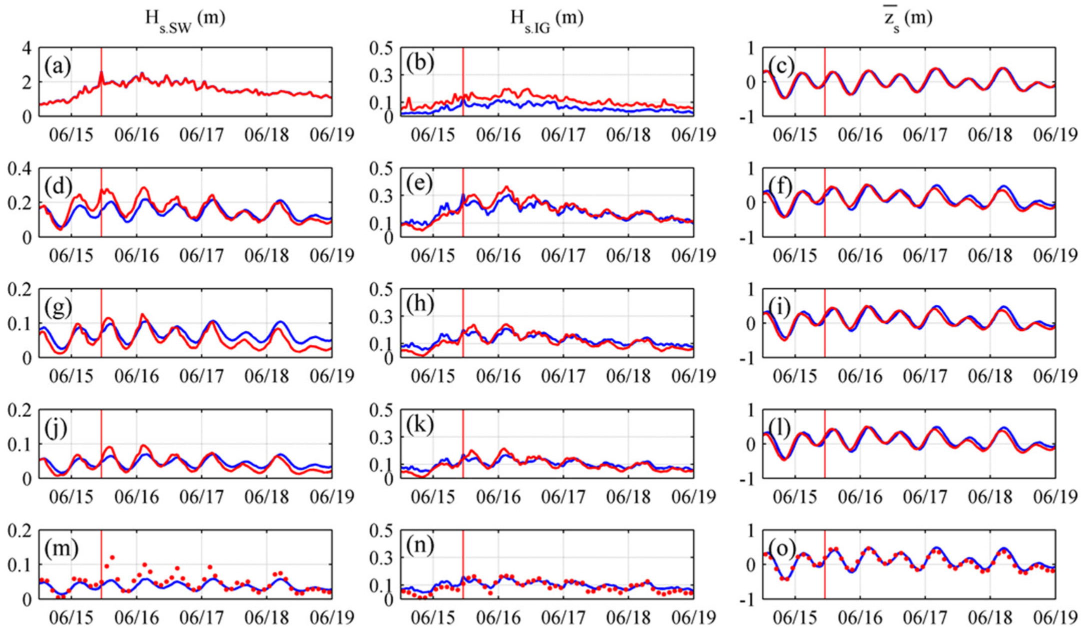

Figure 6. Model (**black**) and data (**red**) comparison for swell wave heights (**left column**), long waves (middle column) and residual (tidal) water level (**right column**) for a five-day period. The rows indicate (**from top to bottom**) the offshore station and subsequent stations on the reef towards to coast, see Figure 6 (**top right**). The results show that the model shows the tidal signature of the swell and long wave variation on the reef, and that variance levels are generally well-predicted.

6. Consequences of Long Wave Dynamics on Port Operations

As shown above, reef topographies can generate long waves which can dominate the swell waves in terms of variance. These waves can have economic consequences by affecting moored ship operations severely. When contemplating solutions to mitigate the impact of the long wave problems in the port of Geraldton, these may be addressed from two sides: from the load side (waves) and the strength side (mooring). The former will be discussed here.

The outright solution by prevention or mitigation of moored vessel problems to IG wave forcing is not evident, as is exemplified by the many studies performed in order to understand the problem and support possible solutions. Possible solutions may be classified in terms of source, pathway, and receptor.

The source of the long waves are the swells generated in the Southern Ocean and the subsequent IG wave generation. Obviously, very little can be done to suppress the generated waves besides drastic (large-scale) measures of altering the reef shape, which will not be practically feasible and it has unknown consequences.

The pathway of the long waves to the receptor—the vessel—can be separated into three parts:

6.1. The Approach Channel

As shown in Figure 5, long waves do not propagate in the channel but rather propagate in the shallows along the channel edge. The gradients in the reef topography thus act as a wave guide since long waves refract towards the shallows and are prevented to propagate over abrupt gradients from the shallows into the deeper channel and deeper reef. Mitigating the problem by changing the channel alignment or dimensions (widening, flattening of the channel or reef slopes) is a potential solution but will come at considerable financial and ecological costs. Potential solutions in the form of wave focusing or defocusing mounds will not work because their design is optimal for a specific combination of wave conditions and directions only, and may worsen the wave climate for other offshore wave conditions.

6.2. The Port Breakwater

Some studies performed for the GPA consider a breakwater extension as a potential solution. The hypothesis is that an extended breakwater would prevent the IG waves from entering the port. This is partly true if the western breakwater is extended, as shown in a number of studies by MetOcean Solutions. However, the breakwater extension primarily results in a reduction of high frequency LW (0.015–0.04 Hz) and to a lesser extent in a reduction of the low frequency LW (0–0.015 Hz). Extending the eastern breakwater exhibits the downside of this solution namely that the IG energy that does enter the port is prevented from radiating out of the port basin, and therefore increasing problems (also shown by MetOcean Solutions, not repeated here). Based on these results, it may be expected that an even longer breakwater will result in a further reduction of wave heights, but clearly at the expense of larger capital costs.

6.3. The Port Basin

Once long waves enter the port basin they may excite resonant frequencies of the basin. These are determined by the port layout and dimensions. It is possible to change the resonant response by deepening the harbor or enlarging the dimensions, but this only shifts the resonant frequencies, and if the adjustments are small only slightly so. Only very large scale layout changes, such as removing the eastern peninsula south of the existing eastern breakwater, will show significant effects on resonance frequencies. The benefit-cost ratio is therefore small. A possible solution is the application of wave damping under the harbor quays. This damping needs to be made of rubble mound or concrete structures and have a sufficient length in order to have an effect on these very long waves. This solution appears practical in case of new quays to be constructed. Given the fact that little can be changed in the IG wave forcing or at the expense of high costs, we expect that the more promising solution is to dampen the vessel's response to incoming IG wave forcing and therewith the loads in the mooring arrangement. A major shortcoming is in the coupling between the IG and swell waves in the port and the ship. It appears that all studies in the survey assume a head-on coupling based on a propagating wave (*i.e.*, waves are incident on the bow of the ship) while in reality the coupling is much more complex (multiple wave directions, standing waves). Therefore, sophisticated model tools as developed in the JIP HAWAII project (Joint Industry Project—sHAllow WAter InItiative) may be applied.

7. Conclusions

This paper reviews the dynamics of infragravity (long-period) waves over reef systems and the consequences of these waves for operations in ports located behind reefs with particular attention to Western Australia. Swells which originate in the Southern Ocean generate long (infragravity) waves, which propagate to the coast. On the reef edge, the swell waves are largely dissipated, transferring energy to turbulence and heat but also in that process generating long wave energy. The remaining swell waves are dominated by the infragravity waves and propagate towards the mainland and into port basins where they cause moored ship motions with consequences for the operational downtime of the port's operations. When contemplating solutions to mitigate the impact of the long wave problems, these may be addressed from two sides: from the load side (waves) and the strength side (mooring).

Numerical models that can be applied to describe the long wave phenomena are in the Boussinesq-type or wave-group resolving class. Other types of models such as wave action models, do not capture the essential physics. While long wave transformation needs to be understood, the potential solutions by changing the pathway to mitigate long wave impact on a vessel are limited and/or costly.

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